UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

HYDROLOGY OF THE JACKPILE URANIUM MINE, NORTHWESTERN NEW MEXICO, AS RELATED TO RECLAMATION OF DISTURBED-SURFACE AREAS

U.S. GEOLOGICAL SURVEY

OPEN FILE REPORT

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CONVERSION FACTORS

Inch-Pound	Multiply by	Metric
inch (in)	2.540	centimeter (cm)
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.09290	square meter (m^2)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilomter (km^2)
foot squared per day (ft^2/day)	0.0929	meter squared per day (m^2/day)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon (gal)	3.785	liter (L)
gallon per minute (gpm)	0.06309	liter per second (L/s)
pound (lb)	0.4536	kilogram (kg)

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ABSTRACT

Reclamation of the Jackpile mine in northwestern New Mexico includes backfilling parts of three open pits, and modifying the shapes of about 32 waste-rock piles. The reclaimed land is intended for livestock grazing. Uranium was mined from the Jackpile sandstone (of economic useage) in the upper part of the Morrison Formation from 1953 to ~~1980~~ 1982. Primary hydrologic concerns are that oxidation and large surface area of waste rock may promote above-normal dissolution of rock minerals by water. Little is known about the quality of water flowing through the waste, however. The climate is arid. Mean annual rainfall is 9.5 inches, and evapotranspiration losses are about 98 percent of rainfall.

The mine area is drained by the Rio Paguate and its tributary, the Rio Moquino. The Rio Paguate flows into the Paguate reservoir, then into the Rio San Jose about six miles south of the Jackpile mine. Mean annual discharge in the Rio Paguate is about 430 cubic feet per second, about half of which is ground-water discharge. Sediment has nearly filled the Paguate reservoir, but less than one percent is estimated to have resulted from mining activity.

The annual recharge rate is about 0.1 inches in the 107 square mile drainage area above the mine. Recharge to rocks in the Jackpile mine is from higher areas to the west, and probably from the north. Some recharge may occur locally in the mine. Most of the shallow, local ground-water flow discharges to mine pits, to underground mines presently being dewatered, and to streams.

Sulfate concentration is the limiting factor for use of stream water in the mine area as a public supply. Concentrations of minor elements and radionuclides are below maximums recommended for use as a public supply, except for a few locations where some samples exceeded limits for manganese, boron, selenium, or radium 226.

Mine pits are presently sinks for ground-water discharge. Part of the pit backfill will saturate after reclamation, and the lower part of waste piles could periodically saturate. Discharge from waste rock will then be to the Rios Moquino and Paguate, to alluvial and aeolian deposits, and possibly to rocks in the Morrison Formation. Post-reclamation, water-table equillibrium levels in waste rock are not known. Above-normal concentrations of dissolved material could be injested by livestock using ponds on backfill, if equillibrium levels are above the pit-backfill surface. Computer ground-water models should be used to describe water-table equillibrium levels in bacfill and waste piles, and to estimate volumetric discharge from the waste rock.

INTRODUCTION

Purpose, scope and description of study

The purpose of this report is to describe the hydrologic conditions in the area of the Jackpile uranium mine, which is located near the town of Laguna, in northwestern New Mexico (fig. 1). The information will be useful for reclaiming disturbed surface areas, and for establishing a hydrologic monitoring system at the mine. The scope of the report consists of description of the ground-water and surface-water systems, including rate and direction of flow, and water quality. The study was conducted primarily by review of available data and reports. Field data collected specifically for this report consisted of measurements of pond altitudes in pits, head measurements at 34 wells on the mine property, results of aquifer tests at five wells, and stream-channel geometry.

Jackpile mine history

Information described in this section was obtained from a report prepared by the Anaconda Copper Company (1980). The mine consists of approximatley 7500 acres of land on the Laguna Indian Reservation. The land is leased from the Pueblo of Laguna by the Anaconda Copper Company. Over 356 million tons of material have been moved since mining began in 1953, including 22 million tons of ore. The mining has affected 2656 acres of land, of which 485 acres have been reclaimed. ~~All disturbed area is~~ ANACONDA PROPOSES to be reclaime~~d~~, with the intention of using the reclaimed land for grazing. The disturbed area consists of: 1015 acres of open pits; 1266 acres covered by 32 piles of waste rock; 185 acres underlain by ore stockpiles, and; 190 acres of supporting facilities:

Ore was excavated by the open-pit method from 1953 to late 1980. The open-pit areas consist of; the Jackpile pit (first area mined), located at the eastern section of the mine, and; the north and south Paguate pits, located at the northwest and west-central part of the mine. Underground mining started in 1974, and has continued to the present (March, 1981). Most underground mines are located in the southwestern section of the Jackpile mine area.

Population centers

The populations centers nearest to the Jackpile mine and their locations relative to the mine are: the village of Paguate about 0.1 mi to the west, and; the villages of Bibo and Moquino, 2 mi to the north. Laguna and Mesita are near the Rio San Jose about 6 to 7 mi to the south. Laguna is above the confluence with the Rio Paguate, and Mesita is below this confluence. The nearest city is Albuquerque, located about 60 mi (by road) east of the mine.

Acknowledgements

Several U.S. Geological Survey personnel made significant contributions to this report, and are acknowledged as follow. Jack Dewey estimated sediment transport rates in the Rio Paguate drainage basin. Discussions with Dick Hadley were helpful in assessing principal factors associated with sediment deposition in reservoirs. Pat Borland estimated flood frequencies for the local streams. Herb Mendietta organized the available chemical data, and described water quality. Several personnel in the Albuquerque office participated in collecting and analyzing aquifer-test data, particularly Paul Davis and Jim Basler.

Anaconda Copper Company personnel provided access and guidance through all areas of the Jackpile mine. Bill Griego of Anaconda Copper Company assisted in collecting head data from wells.

TOPOGRAPHY AND DRAINAGE

Prominent topographic features in the area of the Jackpile mine are the San Mateo Mountains and numerous mesas (fig. 1). The highest point is Mount Taylor, at altitude 11,300 ft, and located about 15 mi northwest of the Jackpile mine. Wheat Mountain (altitude 7140 ft) and the southern flanks of Mesa Chivato are topographically high areas in the immediate vicinity of the mine. Within the lease boundary, altitudes range from 5820 to 6910 ft. The prominent features in the mine are Gavilan Mesa at the northeast corner, and North and South Oak Canyon Mesas along the western edge. Other features are several smaller unnamed mesas, and numerous piles of waste rock and stockpiled ore.

Drainage through the Jackpile mine is by the Rios Paguate and Moquino, whose headwaters are in the San Mateo Mountains (fig. 1). The Rio Moquino becomes part of the Rio Paguate near the center of the mine. The Rio Paguate flows southeast into Paguate Reservoir, then joins the Rio San Jose about 5 mi below the southern boundary of the mine. The Rio San Jose is the main stream in the Laguna area, and flows into the Rio Puerco about 25 mi southeast of its confluence with the Rio Paguate.

The dam at Paguate Reservoir was constructed in 1940, and the reservoir has since been almost filled with sediment. Presently, water ponds only immediately in the vicinity of the dam and spillway.

GEOLOGY AND HYDROLGOIC UNITS

Igneous rocks exposed in the Laguna area are of late Tertiary to Quaternary age, and consist of basalt plugs and basalt flows interstratified with alluvial and pyroclastic deposits. Older, diabase dikes and sills occur locally; two of which may be clearly seen at the walls of the Paguate pits. Mount Taylor is a stratified volcano, and is part of a northeast-trending belt of basaltic cones, plugs, and flows. Interstratified pyroclastic deposits and basalt flows form the cap on Mesa Chivato (Moench and Schlee, 1967) and pyroclastic deposits form the top of Wheat Mountain.

Surficial deposits consist of gravel pediments on the side and base of Mesa Chivato, colluvial deposits on the sides and bases of the mesas, and eolian and alluvial deposits on mesa tops and valley bottoms. Extensive talus, landslide deposits, and sheets of debris cover the steep hillsides at the western edge of the Jackpile mine, and extend continuously along the eastern flanks of Mount Taylor, from Wheat Mountain to Mesa Chivato. These deposits cover parts of North and South Oak Canyon Mesas.

Sedimentary rocks exposed in the Laguna area are, in ascending order: the Chinle Formation of Late Triassic age, the Entrada Sandstone, Todilto and Summerville Formations, Bluff Sandstone, and Morrison Formation of Late Jurassic age; and the Dakota Sandstone, Mancos Shale, and Mesaverde Group of Cretaceous age. The exposed column totals about 3,800 ft in thickness, of which about 1,300 ft is Jurassic strata (Moench and Schlee, 1967). The rocks dip northwestward at about 90 ft/mi in the Jackpile mine area, as determined from structural contours drawn on the base of the Dakota Sandstone by Schlee and Moench (1963). Few faults are present in the mine.

Rocks exposed in and immediately around the Jackpile mine are: the Brushy Basin Member, which is the uppermost Member of the Morrison Formation and is exposed at the bases of some mesas; the Dakota Sandstone, and; the Mancos Shale, which forms the tops of the locally high mesas. The uppermost part of the Brushy Basin Member is predominantly sandstone in the mine area. The sandstone is both the ore-bearing body and the principal local bedrock aquifer. It is called the Jackpile sandstone (of economic useage).

The Jackpile sandstone mostly is fine to medium grained, poorly sorted to moderately well sorted, and friable. It is predominantly detrital quartz, and has a chalky white cast due to kaolinization prior to deposition of the Dakota Sandstone. Moench and Schlee (1967) observed discontinous strata of greenish-gray bentonitic mudstone in most exposures of the Jackpile sandstone. They also stated that it is predominantly calcite cemented in its lower part, and becomes increasingly clay cemented toward the upper part. Its thickness in the Jackpile mine ranges from 40 to 200 ft, with average of approximately 100 ft (Hydro-Search, Inc., 1981, fig. 3).

The Jackpile sandstone is overlain by tightly cemented sandstone in some areas, but elsewhere it is overlain by black shale. The black shale may represent a facies change in the Dakota Sandstone, or it may be a tongue of the Mancos Shale. In this report it will be called a shale in the Dakota Sandstone. The Dakota Sandstone is overlain by beds of tightly cemented sandstone and black shale in the Mancos Shale. Both formations overlying the Jackpile sandstone are extensively fractured. Fracture spacing at outcrops is only a few feet. Underlying the Jackpile sandstone is a mudstone unit in the Brushy Basin Member. In some areas, the mudstone is composed of fine sand to silt-size fragments embedded in a clay matrix, but in other areas it is composed predominantly of swelling-type clays (Moench and Schlee, 1967).

The Dakota Sandstone and Mancos Shale vary in thickness in the Jackpile mine, depending mostly on the topography. The Dakota Sandstone averages about 45 ft. The Mancos Shale is not present on lower mesas, but is about 50 to 75 ft thick at the northwest and west-central part of the mine, and up to about 300 ft thick on Gavilan Mesa. The mudstone unit in the Brushy Basin Member is about 200 ft thick.

The lower hydrologic boundary in the local ground-water system is probably the mudstone unit underlying the Jackpile sandstone, as will be discussed later in the report. Recharge through fractures may occur in the otherwise poorly permeable rocks overling the Jackpile sandstone aquifer. The recharge may occur locally in the mine area, as well as at higher altitudes where these rocks are buried beneath other sedimentary rocks and more permeable colluvial debris and pyroclastic deposits. Most recharge probably occurs at the higher altitudes north and west of the mine, where there is likely to be more rainfall and less evapotranspiration. Few data are available regarding recharge in the Laguna area, however.

Other hydrologic units are the alluvial deposits along valleys, colluvial deposits at the sides and bases of mesas, and basalt flows and pyroclastic deposits in the Mount Taylor and Mesa Chivato areas. Lyford (1977) described springs flowing from the basalt caps on Mesa Chivato, at the upper reaches of the Rio Paguate. It is likely that these springs, combined with flow from colluvial debris along the sides of Bear Canyon on Mesa Chivato, sustain base flow in the Rio Paguate. Similar conditions in Seboyeta and Bibo Canyons farther to the north probably produce the base flow in the Rio Moquino.

CLIMATE

The climate of northwestern New Mexico is characterized by low rainfall and high evapotranspiration. Precipitation data were used from three stations operated by the U.S. Weather Bureau in the Laguna area. The stations are located (fig. 1) at the following towns, with altitudes: Laguna, about 7 mi south of the Jackpile mine at 5800 ft; San Fidel, about 12 mi west of Laguna at 6100 ft, and; Marquez, about 13 mi northwest of the Jackpile mine at 7800 ft. Los Lunas data is also used, because it is long term and several years of pan evaporation data are available at this location. Los Lunas is located about 45 mi southeast of the Jackpile mine, at altitude 4800 ft.

Annual precipitation and years of record are shown in table 1. The rainfall is low, but quite variable. For example, the range for Laguna is from 1.96 in (1956) to 18.42 in (1941).

Table 2 shows mean monthly and mean annual rainfall at the four stations. Only complete years of record were used in computing monthly means. About 60 percent of the rainfall occurs during the five months from May through September, with greatest rainfall in July, August and September. Mean annual precipitation is similar at Laguna and San Fidel. Rainfall at these two stations is about 15 percent greater than at Los Lunas, and about 20 percent less than at Marquez.

Table 1. Annual rainfall at four stations in western New Mexico. All values are in inches. Data from State of New Mexico, 1956, and annual publications of rainfall by the U.S. Department of Commerce.

Year	Los Lunas	Laguna*	San Fidel	Marquez	Year	Los Lunas	Laguna	San Fidel	Marquez
1891	16.37	-	-	-	1936	5.13	7.88	8.90	-
1892	6.11	-	-	-	1937	7.72	8.59	7.86	-
1893	8.40	-	-	-	1938	4.67	7.55	8.53	-
1894	4.55	-	-	-	1939	7.70	9.37	12.34	-
1895	-	-	-	-	1940	11.08	13.54	14.91	-
1896	7.65	-	-	-	1941	-	18.42	22.64	-
1897	-	-	-	-	1942	-	6.00	6.31	10.38
1898	-	-	-	-	1943	-	8.43	9.38	15.51
1899	-	-	-	-	1944	-	11.10	-	14.55
1900	8.05	-	-	-	1945	-	4.43	-	9.69
1901	-	-	-	-	1946	-	-	-	10.85
1902	-	-	-	-	1947	-	-	-	13.46
1903	-	-	-	-	1948	-	-	-	-
1904	10.45	-	-	-	1949	-	8.14	-	13.12
1905	-	-	-	-	1950	5.23	4.03	-	5.22
1906	11.67	13.05	-	-	1951	4.80	4.75	5.82	8.95
1907	15.85	-	-	-	1952	6.34	6.46	8.90	12.32
1908	5.27	8.35	-	-	1953	-	3.73	6.36	9.64
1909	4.25	10.60	-	-	1954	-	8.21	8.72	10.95
1910	-	9.08	-	-	1955	7.89	7.25	6.78	9.12
1911	11.57	12.90	-	-	1956	2.87	1.96	-	5.21
1912	5.47	-	-	-	1957	8.18	13.12	10.39	19.56
1913	7.77	8.68	-	-	1958	6.25	8.72	9.27	16.05
1914	10.21	-	-	-	1959	8.74	10.74	19.07	12.70
1915	12.13	-	-	-	1960	7.71	6.28	8.49	12.27
1916	10.14	-	-	-	1961	8.26	8.53	8.61	13.08
1917	2.15	-	-	-	1962	6.36	9.19	7.85	11.73
1918	9.94	-	-	-	1963	6.34	7.63	8.10	9.12
1919	10.84	-	-	-	1964	6.34	10.30	7.72	9.45
1920	6.27	13.81	-	-	1965	10.17	10.92	-	13.14
1921	9.26	-	10.35	-	1966	5.50	8.67	7.91	7.90
1922	3.24	-	3.15	-	1967	8.93	8.86	10.16	13.37
1923	9.07	-	15.89	-	1968	8.43	7.83	7.83	7.00
1924	5.83	-	4.93	-	1969	10.31	15.44	10.16	12.67
1925	8.37	-	8.55	-	1970	5.90	-	7.70	6.56
1926	8.11	-	10.78	-	1971	7.83	8.69	7.81	7.18
1927	9.40	8.66	13.06	-	1972	13.37	13.74	13.54	11.44
1928	10.26	8.65	11.10	-	1973	10.17	8.17	7.54	8.59
1929	14.07	12.94	12.25	-	1974	11.12	10.40	10.16	8.17
1930	5.08	7.14	7.95	-	1975	5.99	11.92	8.84	-
1931	10.44	-	14.68	-	1976	5.42	7.95	-	-
1932	10.15	-	12.83	-	1977	8.18	11.57	-	-
1933	7.30	14.64	11.98	-	1978	9.75	10.65	-	-
1934	4.34	-	7.23	-	1979	8.19	10.36	-	-
1935	6.07	-	13.93	-	1980	7.53	8.66	-	-

*Rainfall recorded prior to 1891 was: 1850 - 9.69 in and 1851 - 15.12 in.

Table 2. Mean monthly and mean annual rainfall at four stations in western New Mexico. All values are in inches. Data from State of New Mexico, 1956, and annual publications by the U.S. Department of Commerce.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Los Lunas	0.35	0.32	0.45	0.47	0.58	0.56	1.11	1.50	1.11	0.89	0.31	0.42	8.06
Laguna	0.36	0.47	0.43	0.39	0.60	0.60	1.74	1.73	1.40	0.92	0.34	0.50	9.48
San Fidel	0.24	0.37	0.39	0.22	0.41	0.36	1.45	2.12	1.29	1.29	0.24	0.44	9.36
Marquez	0.57	0.29	0.50	0.73	0.63	0.79	1.56	2.95	1.22	0.81	0.54	0.65	11.22

All Laguna data were used for plotting cumulative departure from mean annual rainfall after the year 1919 (fig. 2). Some data from other stations were used for years of incomplete record at Laguna. Mostly, data from San Fidel was used to fill in gaps of missing record, but precipitation at Los Lunas and Marquez was used for some years. The 15 to 20 percent difference between the Laguna and the Los Lunas - Marquez data, and the few years of data used from the latter stations, are assumed to introduce negligible error in cumulative departure for the Laguna area. Monthly data from Laguna and Marquez were combined to obtain a total of 13.67 in for the year 1948.

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A 9.5 in normal was used for the period 1919 through 1980. This is considered a reasonable approximation for the Laguna area, because mean annual rainfall at Laguna is 9.48 in, and the mean for all values on the cumulative departure plot is 9.54 in. Departure from normal in 1919 is assumed to be zero. Precipitation was near-normal for most years in the period 1919 to 1930 (fig. 2), whereas it was: above normal for most of the period 1930 to 1948 and 1968 through 1978, and; below normal for most of the period 1948 to 1968.

Precipitation frequencies (table 3) range, on average, from 1.2 in per 24 hour period every 2 years to as much as 2.8 in per 24 hour period every 100 years.

Table 3. Precipitation frequencies for the Jackpile mine area, New Mexico. Data from U.S. Department of Commerce (1967).

2 year, 24 hour	5 year, 24 hour	10 year, 24 hour	25 year, 24 hour	50 year, 24 hour	100 year, 24 hour	5 year, 6 hour	10 year, 6 hour	25 year, 6 hour	50 year, 6 hour	100 year, 6 hour
1.2	1.6	1.9	2.3	2.6	2.8	1.3	1.6	1.8	2.1	2.2

Monthly pan evaporation for Los Lunas is shown in table 4, and that for Laguna is shown in table 5. Mean monthly pan evaporation ranged from about 0.5 to about 2 in less for most months during the period April through November at Los Lunas, as compared to the means for the same months at Laguna. Maximum difference is only 16 percent between monthly means however, with most months having less than 8 percent difference. In this report, the mean annual pan evaporation at Laguna is assumed equal to that at Los Lunas, which is about 76 in. More than 60 percent of annual pan evaporation occurs during the period May through September. Months of greatest evaporation correspond to months of greatest rainfall, and this compounds the problem of aridity in the area.

Table 4. Monthly pan evaporation at Los Lunas, New Mexico. All values are in inches. Sum of monthly means from all data is 75.52 in. Data obtained from annual publications by the U.S. Department of Commerce.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1962	-	-	-	-	-	-	-	-	6.79	5.00	-	-
1963	-	-	-	10.34	10.96	11.63	11.25	9.87	7.49	4.61	-	-
1964	-	-	-	8.13	12.13	12.83	11.17	9.89	6.66	-	-	-
1965	-	-	-	8.24	10.82	10.23	10.99	9.02	7.12	4.92	-	-
1966	-	-	5.70	9.04	11.81	11.39	10.28	9.70	6.39	5.40	-	-
1967	-	-	7.02	9.64	10.47	11.00	10.41	7.88	6.36	5.90	-	-
1968	-	-	-	9.19	10.24	13.55	12.07	9.91	7.62	5.01	-	-
1969	-	-	4.00	6.22	9.07	10.77	9.30	11.29	4.91	4.87	1.81	-
1970	-	-	4.94	10.47	10.53	10.29	9.48	9.73	6.90	2.77	-	-
1971	-	-	-	8.27	8.58	11.47	12.07	9.37	7.52	3.01	-	-
1972	-	-	-	7.96	8.23	9.74	10.84	9.22	6.60	2.57	-	-
1973	-	-	2.48	3.79	8.33	10.64	9.73	9.39	6.68	4.54	-	-
1974	-	-	7.17	8.20	10.30	11.91	11.07	8.31	-	4.59	2.57	-
1975	-	-	5.64	7.89	9.09	9.53	8.40	9.15	-	5.56	-	-
1976	-	-	-	7.94	9.32	10.72	9.94	8.50	6.00	4.66	3.04	-
1977	-	2.79	5.75	6.75	9.82	10.18	9.83	9.07	5.88	4.76	3.47	2.53
1978	2.00	2.99	5.11	8.99	9.01	10.38	9.90	9.96	7.45	4.71	2.09	-
Mean*	2.00	2.89	5.31	8.19	9.92	11.02	10.42	9.39	6.69	4.56	2.60	2.53
Mean**	-	-	-	8.47	9.38	10.54	9.83	9.00	6.44	4.86	2.09	

*All months of record, with single values assumed equal to mean.
**Only months for which data was also obtained at Laguna, New Mexico.

Table 5. Monthly pan evaporation at Laguna, New Mexico. All values are in inches. Data obtained from annual publications by the U.S. Department of Commerce.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1974	-	-	-	-	-	12.54	10.90	8.92	6.90	3.78	-	-
1975	-	-	-	-	-	13.09	10.19	9.78	-	-	-	-
1976	-	-	-	8.76	11.26	13.09	11.52	9.59	5.88	5.36	-	-
1977	-	-	-	-	10.89	11.22	10.31	9.56	6.77	5.56	-	-
1978	-	-	-	9.33	9.83	12.79	11.98	9.77	7.24	5.92	2.20	-
Mean	-	-	-	9.05	10.66	12.55	10.98	9.52	6.70	5.16	2.20	-

WATER USE

Data regarding water use were obtained from a report by Lyford (1977). Ground water on the Laguna Pueblo is used for public supply, livestock, and industry. Public supplies are obtained from one well near Mesita, and two wells near Paguate. Most wells drilled for individual household use have been abandoned, in favor of better-quality water from public-supply wells.

Surface water from the Rio Paguate is used for irrigation near the village of Paguate. Above Mesita, water from the Rio San Jose is used for irrigation on the Pueblos of Laguna and Acoma.

YIELD AND DEPOSITION OF SEDIMENT AT PAGUATE RESERVOIR

Sediment has nearly filled the Paguate reservoir (location shown on figure 1) since construction of the dam in 1940. The Laguna Pueblo are concerned that operation of the Jackpile mine may have increased the volume of sediment deposited in the reservoir. Three principal factors should be considered in studying reservoir sedimentation. These are: rate of sediment transport, rate of sediment deposition, and trap efficiency (proportion of sediment inflow retained by the reservoir).

Dames and Moore (1980) used sediment volume and rates of sediment deposition, as determined from topographic maps made at different times, to evaluate influence of the Jackpile mine on sedimentation in the Paguate reservoir. Their mean rates of deposition computed for the following periods were: 71 acre-ft/year from 1940 to 1949, and 22 acre-ft/year from 1949 to 1980. Based on the latter rate, the volume of sediment deposited since mining began (in 1952) until 1980 is 620 acre-ft. This is 47 percent of the total 1333 acre-ft accumulated. Dames and Moore (1980) conclude: operation of the Jackpile mine did not cause more rapid deposition of sediment in the Paguate reservoir than occurred before the mine was established, and; sediment accumulated more rapidly before the mine was established than after it was established.

The above conclusions are valid, in regard to the mean rates of deposition for the two time periods discussed. They do not address the basic problem however, which is whether or not the volume of sediment deposited in Paguate reservoir was increased due to operation of the Jackpile mine. The greater rate of deposition in the period 1940 to 1949 was likely due to: (a) greater sediment transport in early years due to above-normal precipitation (figure 2) - rainfall in 1941 was 18.42 in, which is the greatest in all 55 years of record at Laguna (table 1), and (b) much greater trap efficiency in earlier years - efficiency would have been 100 percent during the time the reservoir was filling with water.

The rate of sediment transport, which is sediment yield, has not been measured in the Rio Paguate drainage basin. An approximate yield was therefore computed by using a method described by Shown (1970), in which ratings are placed on several characteristics affecting yield (table 6).

Table 6. Rating ranges for the factors evaluated in the Pacific Southwest Inter-Agency Committee method for estimating sediment yields using terrain characteristics. Modified from Shown (1970).

Factor	Rating range	Main characteristics considered
A. Surface geology	0-10	Rock type, hardness, weathering, fracturing.
B. Soils	0-10	Texture, aggregation, salinity, caliche.
C. Climate	0-10	Storm frequency, intensity, duration.
D. Runoff	0-10	Volume per unit area, peak flow per unit area.
E. Topography	0-20	Steepness of upland slopes, relief.
F. Ground cover	-10-10	Vegetation, litter, rocks.
G. Land use	-10-10	Percentage cultivated, grazing intensity, logging, roads.
H. Upland erosion	0-25	Rills and gullies, landslides.
I. Channel erosion and sediment transport	0-25	Bank and bed erosion, flow depths, active headcuts, channel vegetation.

Ratings were made for the: enitre Rio Paguate drainage basin; Jackpile mine before mining, and; Jackpile mine in its present condition (table 7). Drainage is into closed basins (pits) for 5.0 mi^2 of the 6.0 mi^2 in the mine area. The ratings for the present conditions apply to the 1.0 mi^2 with external drainage.

Shown (1970) described the correspondence of ratings and estimated sediment yields (in acre-ft/year/mi^2) as: rating 25 to 50 gives yield of 0.2 to 0.5, and; rating of 100 to 125 gives yield of 3.0 to 7.0. Ratings in table 7 were summed for each drainage area and the corresponding yields computed (table 8). The net sediment yield due to mining operations is therefore estimated as the difference between yields before and after mining, which is 3.5 - 3.0 = 0.5 acre-ft/year. The estimated present rate of sediment yield due to mining is therefore only about 1.0 percent of the 46 acre-ft/year total yield in the basin. This percent may be too large if used to compute total yield since mining began, because a smaller mined area was exposed during the early years of operation.

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Table 7. Descriptions of characteristics and ratings for estimating sediment yield in the Rio Paguate drainage basin.

Factor*	Rating	Description
		Total Rio Paguate drainage basin above the mine
A	5	Rocks are of medium hardness, moderatly weathered, and fractured.
B	5	Soils are medium textured with occassional rock fragments.
C	8	Most runoff is due to intense convective storms, but is low in volume.
D	5	Runoff occurs as high peaks, but has low volume.
E	12	The average upland slopes are less than 30 percent, but there is little floodplain.
F	-5	Upper areas have good ground cover and the lower areas have moderate ground cover.
G	-10	Little cultivation, little recent logging, and low intensity grazing.
H	5	Signs of erosion on less than 25 percent of the land surface.
I	15	Active headcuts and degradation in tributary channels, but flow duration is short.
		Jackpile mine area before beginning mining operations
A thru E		Same as described above.
F	0	Lower areas have moderate ground cover.
G and H		Same as described above.
I	20	Headcuts and degradation are more prevalent in lower reaches.
		Jackpile mine area in present condition
A thru D		Same as described above.
E	20	External drainage is mostly from the steep slip faces on the outsides of the waste piles.
F	10	Very little ground cover.
G	10	Land use high.
H	25	Rills cover about 50 percent of the land surface.
I	15	Much of the sediment eroded from the slip faces is deposited at the bottoms of the faces.

*Correspond to factors in table 6.

Table 8. Estimates of sediment yield in the Rio Paguate drainage basin.

Drainage area description	Rating total	Unit yield (acre-ft/year/mi^2)	Area (mi^2)	Total yield (acre-ft/year)
Entire Rio Paguate	40	0.38	120	46.0
Mine area before mining began	50	0.50	6.0	3.0
Mine area at present	103	3.5	1.0	3.5

Only part of the approximate 0.5 acre-ft/year yield was actually deposited in Paguate reservoir, because trap efficiency was less than 100 percent during mining. Using the deposition rate of 22 acre-ft/year for the period 1949 to 1980, as determined by Dames and Moore (1980), and the total yield in the Paguate drainage basin, trap efficiency would be about:

(22 acre-ft/year)/(46 acre-ft/year) = 48 percent. Using the 0.5 acre-ft/year (maximum) yield during mining, the mean sedimentation rate during mining would have been less than (0.5 acre-ft/year)(0.48) = 0.2 acre-ft/year.

Trap efficiency would probably apply equally to both mine sediment and total basin sediment, so the proportion of sediment deposited from mining to that deposited from total basin erosion is the same as the proportion for sediment yield, which is about 1.0 percent. The small percent results from the fact that the mine area constitutes a small portion of the total Rio Paguate drainage basin.

Shown (1970) discussed the magnitude of error in using the rating method for estimating sediment yield at sites in Colorado, New Mexico and Wyoming. Most estimated yields tended to be lower than measured yields, and he attributed this to the subjective application of the ratings. The mean sediment-yield estimate for 28 sites was 1.4 acre-ft/mi^2, whereas the mean determined from reservoir records was 1.73, giving a mean error of -19 percent. The maximum error for all sites studied was about -180 percent.

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SURFACE WATER

Stream discharge

Streamflow data were collected on the Rio Paguate, as follow: near the village of Paguate from March, 1937 through September, 1941, and; at the south end of the Jackpile mine from March, 1976 to the present. Locations of the gaging stations are shown on figure 1. Discharge was not measured on the Rio Moquino.

Only complete water years (October through September) are used in this report. A summary of the discharge data is shown in table 9. Mean monthly and mean annual discharge are given in appendices 1 and 2.

Table 9. Summary of discharge data for Paguate Creek near Laguna, New Mexico (1938 through 1941) and Rio Paguate below Jackpile mine near Laguna, New Mexico (1977 through 1980). All values are in cubic feet per second.

Water year	Maximum daily	Mean daily	Minimum daily	Total
1938	-	0.99	0.20	361*
1939	-	1.02	0.40	372*
1940	-	1.02	0.30	372*
1941	-	3.80	0.40	1387*
1977	34	1.48	0.04	539.07
1978	42	1.08	0.07	394.03
1979	14	1.33	0.06	485.94
1980	42	0.87	0.00	316.66
Mean for period 1938 through 1941	-	1.71	0.32	623
Mean for period 1977 through 1980	33	1.19	0.04	433.93

*Approximated by multiplying mean daily discharge by 365 days.

The mean daily discharge for complete years of record at the gaging station near Paguate (1.71 ft^3/s) is influenced considerably by the unusually large value for the year 1941. Rainfall for calendar year 1941 was the greatest on record at Laguna, and caused the anomalously large value. The Rio Paguate usually flows all year. It is occassionally dry at the gaging station below the Jackpile mine, as shown by the minimum daily discharge in table 9-.

The stream discharge is only about 2 percent of the rainfall in the Rio Paguate drainage basin, as will be discussed in the Water Balance section of this report. This illustrtates the extremely large evapotranspiration in the area.

Base flow

In humid areas, ground-water discharge to streams (base flow) is often determined by computing a constant slope from the decreasing limb of the discharge plot (recession), then using this slope as a control for estimating base flow during recessions. In the arid Rio Paguate drainage basin, floods are infrequent during winter months, so that most discharge is base flow during this time. More frequent floods in summer are due to thunderstorm activity that is intense, but of short duration. The recessions are therefore rapid. Their slopes are therefore difficult to determine, not constant, and not completely controlled by ground-water outflow.

Ground-water gradients near the streams are reversed (head is greater in the stream than in the adjacent aquifer) when the stream stage rises, and during the early part of the recession. Base flow during this time is zero. Base flow at the Rio Paguate gaging station is approximated by assuming there is no ground-water discharge during the entire rising and falling stages of the stream. The method is similar to that described by Daniel and others (1970).

Ground-water discharge during recessions is not taken into account for the Rio Paguate, so base-flow values are somewhat low. The error is probably not significant however, because: (a) discharge during much of the falling stage of summer floods is low, compared to greater, predominantly base-flow periods in winter, and (b) some of the discharge during falling stages is from temporary ground-water storage very near the stream (bank storage), whereas the flow of primary interest here is the regional ground-water discharge to the stream.

Most base flow to the Rio Paguate occurs during winter (table 10), and constitutes a large percent of the total flow in the Rio Paguate. For the following years, it was: 1977 - 51 percent, 1978 - 56 percent, 1979 - 35 percent and 1980 - 60 percent.

Table 10. Monthly and annual base flow for Rio Paguate below Jackpile mine near Laguna, New Mexico. All values are in cubic feet per second - days.

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
1977	18.5	29.7	34.1	29.8	37.7	46.1	18.5	38.1	13.8	0.48	0.63	9.10	276
1978	14.1	16.3	29.3	40.0	22.4	43.1	24.1	19.4	7.50	0.77	1.46	2.84	221
1979	3.84	12.3	19.5	11.1	16.0	9.70	40.8	28.4	12.9	1.91	4.39	10.6	171
1980	8.56	16.4	17.4	26.7	31.3	55.9	23.7	5.88	3.11	0.33	0.08	0.43	190
Mean	11.2	18.6	25.0	26.9	26.8	38.7	26.7	22.9	9.33	0.87	1.64	5.74	214

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Flood frequency

Flood frequencies were estimated at three locations near the Jackpile mine: on the Rio Paguate 500 ft upstream from the northwest mine lease boundary; on the Rio Moquino 1500 ft downstream from the northern mine lease boundary, and; on the Rio Paguate 400 ft above the gaging station near the southern mine lease boundary. Streamflow data from the gaging station were used to estimate flood frequency by use of the U.S. Geological Survey flood-flow-frequency program (J407). Two other methods were used for all sites: the basin characteristics method, as described by Thomas (in press), and; the channel geometry method, as described by Scott (1976).

The basin characteristics method involves determination of contributing drainage area and site altitude, then use of the equation $Q_N = (C)(A^x)[(SA/1000)^{-y}]$, where Q_N is peak discharge for N recurrence intervals, C is a constant, A is drainage area, and SA is site altitude. Values for C, x, and y, are presented by Thomas (in press) for different recurrence intervals, as are standard estimates of error which he described as ranging from 98 to 131 percent.

The channel geometry method involves measurement of the active stream-channel width, then use of the equation $Q_t = aW^b$, where Q is the peak discharge for t recurrence intervals, a is a regression constant, and W is active channel width. Values of a and b are given by Scott (1976) for different recurrence intervals to a maximum of 50 years, as are estimates of standard errors which he described as ranging from 62 to 231 percent. Recurrence intervals greater than 50 years were estimated for streams at the Jackpile mine by linear extrapolation on the recurrence interval - discharge plot from earlier years.

Measurements for use in the flood frequency methods are given in table 11. Peak discharges were determined for recurrence intervals of 5, 10, 25, 50, 100, 200 and 500 years (table 12.). Flood frequencies obtained by using the channel geometry method are, on average, about three times less than those obtained by use of the basin characteristics method. Those values obtained by the latter method are probably more accurate than those from the channel geometry method, because: (a) standard estimates of error are smaller for the method, and (b) values obtained by the basin characteristics method more closely approximate those obtained by use of streamflow data in the flood-frequency program.

Table 11. Measurements used for estimating flood frequency in the Jackpile mine area.

Location	Active channel width (ft)	Contributing drainage area (mi^2)	Site altitude (ft)
Rio Paguate above Jackpile mine	10	30.8	6070
Rio Moquino above Jackpile mine	12	68.6	6000
Rio Paguate below Jackpile Mine	20	107	5820

Table 12. Flood frequencies for three sites in the Jackpile mine area.

Recurrence interval (years)	Discharge by flood frequency program (ft^3/s)	Discharge by basin characteristics method (ft^3/s)	Discharge by channel geometry method (ft^3/s)
		Rio Paguate above Jackpile mine	
5	-	762	208
10	-	1180	337
25	-	1890	558
50	-	2590	774
100	-	3370	1000
200	-	4260	1300
500	-	5780	1800
		Rio Moquino above Jackpile mine	
5	-	1140	276
10	-	1740	442
25	-	2730	722
50	-	3700	993
100	-	4780	1300
200	-	5990	1700
500	-	8030	2500
		Rio Paguate below Jackpile mine	
5	1810	1520	609
10	2710	2310	946
25	4150	3610	1490
50	5450	4880	2000
100	6940	6290	2600
200	8670	7860	3300
500	11300	10500	4400

The estimates of flood frequencies may prove useful for design of structures such as road culverts during reclamation of the Jackpile mine. Flood-prone areas could be outlined by using the flood-frequency values. The areas are partly dependent on existing structures in the mine however, and would probably be changed considerably during reclamation of roads, culverts, and other stream constrictions such as waste piles presently in the channels.

Ponding at waste piles

An unnamed valley on the east side of Gavilan Mesa is blocked by waste-rock dumps C, D, E, F, and G (fig. 3). Overland runoff occasionally ponds at the base of the dumps. The ponded water may therefore infiltrate both the valley alluvium and the waste rock. The expected depths of water in the pond are discussed in this section. Ground-water flow is discussed later in the report.

The initial altitudes of ponded water after flood events were computed by: (a) deriving an altitude - capacity curve (fig. 4) from a topographic map, then (b) determining discharge in the valley using the streamflow characteristics method, as described by Borland (1970). The pertinent factors relating to streamflow characteristics in the unnamed valley, and their corresponding values, are: drainage area - 0.97 mi^2; precipitation from October through April - 3 in; longitude - 107 degrees 10 minutes; soils infiltrtation index - 8.5, and; mean basin elevation 6070 ft.

Flood volumes and depths of ponded water are shown in table 13 for different recurrence intervals. Maximum depth is 3.9 ft for a flood flow of one day at recurrence interval of 50 years. Depths are less than 2 ft for most flow periods and recurrence intervals.

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Table 13. Flood volumes and depths of ponded water in valley at east side of Gavilan Mesa.

Floods and recurrence intervals*	Volume (ft^3/s-days)	Volume (acre-ft)	SE** (%)	Altitude of water level (ft)	Depth of water (ft)
$F_{1,2}$	0.29	0.6	59	5996.6	0.6
$F_{1,5}$	0.84	1.7	55	5997.6	1.6
$F_{1,10}$	1.31	2.6	55	5998.2	2.2
$F_{1,25}$	2.13	4.2	60	5999.2	3.2
$F_{1,50}$	2.90	5.8	66	5999.9	3.9
$F_{3,2}$	0.12	0.2	62	5996.2	0.2
$F_{3,5}$	0.34	0.7	56	5996.7	0.7
$F_{3,10}$	0.54	1.1	55	5997.1	1.1
$F_{3,25}$	0.88	1.7	56	5997.6	1.6
$F_{3,50}$	1.17	2.3	60	5998.0	2.0
$F_{7,2}$	0.06	0.1	61	5996.1	0.1
$F_{7,5}$	0.15	0.3	58	5996.3	0.3
$F_{7,10}$	0.24	0.5	56	5996.5	0.5
$F_{7,25}$	0.37	0.7	56	5996.7	0.7
$F_{7,50}$	0.48	1.0	59	5997.0	1.0

*$F_{n,m}$ is flood volume for flow period n, at recurrence interval m: for example, $F_{1,2}$ means flood volume for 1-day period at 2-year recurrence interval.

**Standard error of estimate.

GROUND WATER

Underflow and recharge

An estimate is made of the recharge rate in the Rio Paguate drainage basin by assuming that change in ground-water storage is negligible and summing base flow and umderflow. Underflow may occur in the vicinity of the Rio Paguate gaging station via the alluvium, Jackpile sandstone, and underlying rocks.

Alluvial underflow cannot be determined at the exact location of the gaging station, because data are insufficient. Data are used from wells located near the confluence of the Rios Paguate and Moquino for estimating underlfow at the station. An aquifer test at well M4C (described in a later section) showed hydraulic conductivity (K) of the alluvium to be 22 ft/day. Saturated thickness (b) is about 20 ft and width (w) is approximately 1000 ft. Hydro-search, Inc. (1979) showed the gradient of the stream as about 0.02 at this location. The hydraulic gradient (I) is approximated by assuming it is equal to the gradient of the stream. Underflow is approximated as $Q = KIbw = 9{,}000\ ft^3/day$, which is equivalent to an annual flow of 40 ft^3/s-days. Annual base flow is 214 ft^3/s-days (table 10). Base flow plus underflow through alluvium is therefore about 250 ft^3/s-days annually.

Underflow through bedrock cannot be determined, because data are insufficient. Saturated zones and hydraulic gradients are not known, and hydraulic conductivities of rocks other than the Jackpile sandstone are not known. Positions of ground-water divides may not correspond to topographic divides, so interbasin flow may occur. For purposes of this report, it is assumed that neglecting underflow through bedrock does not introduce significant error in estimating the recharge rate in the Rio Paguate drainage basin. This assumption is probably reasonable, because: (a) the mudstone strata underlying the Jackpile sandstone forms the lower hydrologic boundary over much of the lower part of the basin, and (b) the top of the mudstone outcrops generally northeast-southwest across the basin in the vicintiy of the Rio Paguate stream-gaging station, so that much of the water in the Jackpile sandstone probably discharges to the alluvium or to streams above the station.

The recharge rate is estimated as the sum of base flow and underflow through alluvium, which is 250 ft^3/s-days annually in the Rio Paguate drainage basin above the gaging station. This is equivalent to about 0.1 in/year over the 107 mi^2 drainage area. Rates are probably greater at higher altitudes on Mount Taylor and Mesa Chivato, and may be less at lower altitudes. Recharge is probably greater in colluvium on the flanks of mesas, and in alluvium at valley bottoms, than it is on exposed bedrock.

Wells in the Jackpile mine

Wells were installed for two hydrologic studies at the Jackpile mine. The "P"-series of 11 wells was constructed in 1977 by Hydro-search, Inc. (1979) to examine water-quality effects of holding ponds on the ground-water system. The "M"-series of 30 wells was constructed about 1980 by Hydro-search, Inc. (1981), as part of a general hydrogeologic study. Locations are shown on figure 3 for wells completed in bedrock and waste rock. Seven observation wells were also constructed for aquifer tests of M-wells.

The P-series wells have 2 in diameter PVC casing in the drillholes, which is slotted and gravel packed through the aquifers (Hydro-search, Inc., 1979). Cement depths are not reported for P-wells. Well P5 is presently inaccessible, and well P11 is destroyed. The M-series wells have 5 9/16 in diameter steel casing, which is slotted and gravel packed through the aquifers (Hydro-search, Inc., 1981). The wells were cemented from the tops of the gravel packs to ground surface, except for wells completed in waste rock and well M22 (written communication to Anaconda Company from Hydro-search, Inc., August, 1981).

Most wells are open to the two principal aquifers in the area: the alluvium and the Jackpile sandstone. None are completed solely in bedrock overlying the Jackpile sandstone. Well M25 is completed in the mudstone unit of the Brushy Basin Member underlying the Jackpile sandstone. Wells M17 and M24 are drilled into mine waste rock. Jackpile sandstone intervals penetrated by the wells are given by Hydro-search, Inc. (1979 and 1981).

Figures 5, 6, 7 and 8 are graphs showing well construction, and positions of water levels. The diagrams show equal spacing between wells. They are intended to illustrate relative positions of strata contacts and water levels, and should not be construed as geologic sections. Strata contacts and well depths are from Hydro-search, Inc. (1979 and 1981). Water levels were measured in June, 1981.

Wells in the northern part of the mine (fig. 5) have water levels above the top of the Jackpile sandstone, whereas those in other areas have water levels within this strata. Recharge is primarily from overlying strata to the north and northwest. The dip of the rocks causes the Jackpile sandstone to be below land surface northand west of the mine, resulting in complete saturation. Water levels below the top of the Jackpile sandstone are due to discharge to valleys and mine pits, and probably less recharge at lower altitude.

Potentiometric surface and directions of ground-water flow

Regional ground-water flow in the Laguna Pueblo is southward toward the Rio San Jose, and eastward toward the Rio Puerco (Lyford, 1977). The emphasis of this report is on local flow, and descriptions are based primarily on a potentiometric-surface map of the Jackpile mine.

Water levels and well depths were measured in all wells reported by Hydro-search, Inc. (1979 and 1981) as being completed in bedrock, and two wells completed in waste rock (table 14). Measurements were made with steel tape during the period June 10 through June 12, 1981. Accuracy is about ± 0.05 ft for most wells. It is about ± 0.2 ft for well M20, and about ± 3 ft for well P6. Water-level altitudes are given in tenths of a foot for P-wells, because only ground-surface altitudes at the wells are available. Table 14 also shows altitude differences for water levels measured in earlier studies by Hydro-search, Inc. (1979 and 1981) and those measured for the present study.

The water levels represent composite heads, because the wells are open to many feet of saturated rocks. Wells open to the Jackpile sandstone are used to indicate general directions of ground-water flow and general ground-water gradients in that stratum however, because most are open to the entire thickness of the stratum. Hydro-search, Inc. (1979) measured a water-level at altitude 5960 ft in well P11 (now destroyed) in March, 1979, and this measurement was also used in constructing a potentiometric-surface map for the present report.

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Table 14. Water levels in wells at the Jackpile mine. All values are in feet.

Well	Height of casing above ground level	Depth to water in June, 1981*	Altitude of water level in June, 1981	Difference from previous levels**	Depth of well*
M1	2.0	298.59	6003.61	- 3.01	403.1
M2	1.6	110.30	5962.61	+ 2.18	201.6
M3	1.7	162.68	5924.04	+ 0.22	302.7
M4	2.3	44.83	5896.77	+ 0.65	110.7
M5	2.8	378.52	6014.57	- 1.30	467.7
M6	2.2	170.21	5976.08	-18.66	261.8
M7	2.5	327.59	5940.96	- 0.05	360.1
M8	2.1	162.18	5940.29	- 3.05	217.8
M9	2.2	90.94	5926.98	- 0.29	219.9
M10	2.6	231.47	5959.33	0.00	289.9
M11	2.5	90.93	5912.95	- 0.35	222.4
M12	2.4	173.74	5920.86	- 0.24	201.5
M13	2.5	270.37	5955.53	-	270.8
M14	2.5	199.13	5912.76	- 1.44	324.2
M15	2.3	123.12	5925.70	- 5.22	251.3
M16	2.1	147.47	5911.51	- 0.72	219.4
M17***	2.7	249.02	5867.86	-	254.1
M18	2.2	217.31	5878.95	-	219.3
M19	2.7	274.85	5930.21	+ 0.27	406.9
M20	2.5	180	5925.2	- 0.2	188.4
M21	2.4	114.43	5961.17	- 0.14	204.0
M22	2.8	244.77	5982.64	+ 1.04	290.7
M23	2.3	58.61	5951.52	- 0.93	202.9
M24***	3.0	244.40	5981.45	-	246.9
M25****	1.6	179.34	5906.06	-	-
M26	1.8	38.79	5881.11	- 0.26	67.1
P1	0.5	45.98	5897.9	- 1.8	86.2
P2	2.1	52.70	5923.1	+ 1.3	143.2
P3	0.5	151.93	5921.5	- 2.9	313.4
P4	1.6	57.08	5953.0	- 3.0	171.6
P6	1.4	270	5969	-23	-
P7	1.7	168.52	5942.5	-40.3	269.9
P8	0.7	122.19	5920.5	- 2.0	250.8
P9	2.4	177.33	5912.2	- 9.0	332.7

*Depth referenced to top of casing.
**Water levels measured in December, 1980 (M-wells) and March, 1979 (P-wells) subtracted from those measured in June, 1981.
***Completed in backfill.
****Completed in Brushy Basin Member below Jackpile sandstone.

Well locations and potentiometric surface for the Jackpile sandstone are shown on figure 3. Flow into the mine area is primarily from high areas on the flanks of Mount Taylor to the west, and probably from Mesa Chivato to the north. Much of the flow from the west is intercepted by the North and South Paguate pits, and by pumpage from the P-10 underground mine.

Seepage faces are obvious on the walls of the North and South Paguate pits. The top of a seepage face was at altitude 5948 ft on a waste-covered section of bedrock at the north side of the South Paguate pit, and a pond in the lowest part of the pit had a water-surface altitude of 5927 ft (figure 3). The altitudes were measured in June, 1981. They were below water-level altitudes measured in nearby wells. Water-surface altitudes were not measured in other pits, but the lowermost pond in the North Paguate pit was visually observed to be below the tops of seepage faces. Closed potentiometric contours were therefore drawn around all pits, and indicate ground-water discharge into the pits. Water loss is by evaporation, and use of pond water for wetting roads.

Bedrock edges of pits were drawn, because the pits constitute sinks for ground-water flow. Topographic contours could not be used, because some high areas at pit edges are extensive piles of waste rock. Most cross sections drawn by Anaconda Copper Company (1980) show "edges of excavation", and these are shown on figure 3. The top of the Jackpile sandstone at the approximate pit edge is illustrated where the edges of excavation are not shown on the cross sections. Where neither of the boundaries were reported, the edge is not shown. Both the "edges of excavation" and the edge of the Jackpile sandstone are shown at the northeast end of the Jackpile pit, because the top of the stratum underlies much of the excavated surface at this location. Few detailed cross sections are available for the North Paguate pit, so its boundaries are not shown.

The positions are approximate for the ground-water divides near the pits, because there are few wells at pit edges. Potentiometric contours at pit edges are simplified: with extensive data-point control, many closely spaced contours would be drawn near seepage faces.

Water-table surfaces could not be drawn inside pits, due to lack of data. A pond in the south Paguate pit, with water surface altitude measured at 5976.3 ft (fig. 3) in June, 1981 is higher than the pond in the deeper part of the pit, and higher than water levels in some wells. The higher ponds are probably due to surface runoff and water from near-surface infiltration discharging into them. Infiltrating water from the higher ponds probably flows through backfill material, toward the lower ponds.

Water-level differences shown in table 14 generally show lower heads for the later measurements. Differences of about 2 to 3 ft are probably not significant. They may be due to different measuring techniques, or seasonal changes. Significant head declines in wells M6 (18 ft), P7 (40 ft) and P6 (23 ft) probably result from decreasing heads due to discharge into the North and South Paguate pits. Head changes in well M1, M22 and M7 are small, indicating that pumpage from the P-10 underground mine presently has less influence on heads near wells M6, P7 and P6 than does discharge into the Paguate pits. Discharge into the North Paguate pit probably caused the head declines in wells P3 (3 ft), P9 (9 ft) and M8 (3 ft).

Well M25 (not shown on figure 3) is 50 ft from well M3, and is completed in a sandstone bed underlying a mudstone unit approximately 100 ft thick. The mudstone underlies the Jackpile sandstone in which well M3 is completed. The water level in well M3 was 17.1 ft higher than that in well M25 in August, 1981, indicating downward flow at this location. Well M25 penetrates about 180 ft more strata than well M3 (Hydro-search, Inc., 1981), indicating a gradient of about 0.1 in the vertical.

The local flow system is probably more complex than shown in figure 3. Even though 33 wells are available for control in drawing potentiometric contours in the Jackpile sandstone, data are insufficient to show: influence of local topograpic and mining features; gradients near streams, particularly the Rio Moquino and downstream reach of the Rio Paguate, and; flow in the northern, northwestern, and southeastern parts of the mine.

Potentiometric contours at Gavilan Mesa are highly interpretive, with only wells M19, M20 and M21 for control. Hydro-search, Inc. (1981) drew contours in this area as reflecting flow from the east. There is no apparent recharge area in that direction however, and Gavilan Mesa is the highest area at the eastern part of the mine. Contours are therefore drawn as indicating local recharge through the highly fractured rocks comprising Gavilan Mesa.

The gradients drawn around the northwest and west side of Gavilan Mesa are about one to two orders of magnitude greater than would be expected if a hydraulic conductivity of 0.3 ft/day were used for the Jackpile sandstone (explained in the following section), with a recharge-discharge rate of 0.1 in/year. The water level in well M19 (fig. 5) shows nearly complete saturation of the sandstone at this location, at an altitude of 5930.2 ft. Contours from 5930 to 5960 ft in figure 3 therefore represent saturation of the Dakota Sandstone on the mesa. Observations of outcrops showed the rocks to be tightly cemented, with most effective porosity apparently due to fracturing. Hydraulic conductivity could be two orders of magnitude less than that in the Jackpile sandstone, thus producing gradients approximating those shown.

A well on Gavilan Mesa, completed in the Jackpile sandstone, would show whether or not the interpretation illustrated on figure 3 is correct. Wells at the same location, open only to fractures in the Dakota Sandstone and only to fractures in the Mancos Shale, might show one or more water tables higher than that in the Jackpile sandstone. If so, local recharge might be expected in other areas of the mine, including waste dumps.

The ground-water divide at the 5970 ft potentiometric contours south and east of the South Paguate pit are probably either due to: (a) nonequillibrium conditions resulting from withdrawal in the P-10 underground mine and losses to the South Paguate pit, thus lowering a higher surface present when heads were greater at the western part of the mine, or (b) equillibrium conditions which reflect local recharge. Similar explanations may be made for the ground-water divides at the 5920 ft contours east of the North Paguate pit, and perhaps some areas around the Jackpile pit. Nonequillibrium conditions are likely to prevail over some of the mine area however, as indicated by the recent large changes in some ground-water levels described earlier in this section.

Well M17 is in a waste dump at the southwest end of the Jackpile pit (fig. 3). The dump extends southward to a small mesa on which well M18 is located. Data are insufficient to determine whether flow in the vicinity of well M18 is toward the dump, or toward the Rio Paguate. Potentiometric contours between wells M16 and M18 were therefore truncated.

Streams gain water near the center of the mine, as indicated by the potentiometric contours. Hydro-search, Inc. (1979) described gains of about 20 gal/min near the confluence of the Rio Moquino and Rio Paguate, whereas losses were observed in the Rio Paguate from the western edge of the mine to a point about 1000 ft above its confluence with the Rio Moquino.

The potentiometric surface shown in figure 3 does not reflect losing areas, which would be expected to result in ground-water mounding along the stream. Contours could not be drawn with available data to reflect ground-water mounding, without producing unreasonably large gradients. The stream channel was changed during mining in the vicinity of wells M23 and P4 and, as shown on section 12 by Anaconda Company ("Jackpile-Paugate Mine Additional Cross Sections 1-19", undated), is now underlain by about 40 feet of waste rock. The waste is probably permeable enough so that there is little ground-water mounding.

In summary, normal ground-water flow has been changed in the Jackpile mine by pit excavations, pumpage from underground mines, and probably by streambed alteration. Natural variations in hydraulic conductivity are likely to also produce local changes in flow. Extensive well control would be needed to define the ground-water system accurately. In general, ground water enters the mine primarily from the west and north, and flows mostly toward pits, the P-10 underground mine, and the Rio Paguate and Rio Moquino. Flow in the southeastern part of the mine is not defined, but is probably toward the Rio Paguate, or toward the southeast.

Aquifer Tests

Water-transmitting characteristics of aquifers were determined at four sites in the Jackpile mine. A submersible pump was installed in three wells, and constant-rate pumping continued until completion of tests. A fourth well (M25) was "slug tested", using a piston to increase the head in the well. Head data were collected continuously at each site, from both the pumped well and a nearby observation well. Pressure transducers were used, and readings were verified about hourly by measurements with steel tape.

Strata and sites tested were: the alluvium at the confluence of the Rio Paguate and Rio Moquino; the Jackpile sandstone at the northwest and southwest parts of the mine, and; a sandstone bed in the predominatly mudstone part of the Brushy Basin Member at the northwest part of the mine. Test data were analyzed as follow: wells M2 and M4C by the nonequillibrium method with allowance for delayed yield from storage, as described by Boulton (1963); well M3 by the curve-matching, nonequillibrium method described by Theis (1935), and well M25 by the instantaneous-charge method described by Cooper, Bredehoeft, and Papadopulos (1967).

Description and results of the tests are given in table 15. Distances between discharge and observation wells were obtained from Hydro-search, Inc. (1981). Well locations are shown on figure 3, except for well M4C, which is located 54 ft northeast of well M4. Hydraulic conductivity of the Jackpile sandstone is about 0.3 ft/day. The alluvium has hydraulic conductivity almost two orders of magnitude greater than the bedrock strata tested, probably because of larger interconnected pore size and lack of cementation between grains.

Table 15. Aquifer tests of four wells in the Jackpile mine.

Well	M2	M3	M4C	M25
Strata tested	Jackpile sandstone	Jackpile sandstone	Alluvium	ssBB*
Distance between discharge and observation wells	54	44	52**	-
Date test began	8/19/81	8/24/81	8/22/81	8/19/81
Altitude of water level before test (feet)	5964.6	5924.5	5897.4	5907.4
Maximum drawdown (feet)	37.0	61.6	1.9	-
Duration of test (hours)	43	88	17	2
Pumping rate (gal/min)	5.1	15.3	8.6	-
Saturated thickness (feet)	93	120	19	60
Transmissivity (ft^2/day)	26	47	410	20
Hydraulic conductivity (ft/day)	0.28	0.39	22	0.33
Storage coefficient X 10^4 (dimensionless)	1.9	2.7	19	1.0

*Sandstone bed in predominantly mudstone part of the Brushy Basin Member.
**Observation well used was M4B.

The 0.33 ft/day hydraulic conductivity for the sandstone bed in the Brushy Basin Member at well M25 is probably much larger than that for the mudstone part of the Member. Mudstone beds approximately 100 ft thick separate the sandstone bed from the overlying Jackpile sandstone (Hydro-search, Inc., 1981). Maximum water-level change was 0.16 ft in well M25 when 61.6 ft of drawdown was produced in the Jackpile sandstone after four days of pumping at well M3. Distance is only 50 ft between the two wells. The small head change in well M25 may have been due mostly to change in barometric pressure during the test. The predominantly mudstone part of the Brushy Basin Member probably forms the lower hydrologic boundary in the mine, as indicated by the lack of hydraulic connection with the Jackpile sandstone, and because it underlies the alluvium and stream channels in the area.

The small storage coefficients for the Jackpile sandstone indicate a confined system. Water levels in wells M2 and M3 were below the top of the aquifer, so the Dakota Sandstone did not cause the confined conditions at the well sites. The Jackpile sandstone contains discontinuous strata of bentonitic mudstone, and clay content increases upward in the stratum (Moench and Schlee, 1967). The mudstone and clay cement probably cause local confined conditions.

Flow through backfill and waste piles

Few data are available to accurately describe flow through backfill (in pits) and waste piles (located outside pits). Problems regarding drilling and completing wells in waste rock are described by Hydro-search, Inc. (1981), and these evidently account for the lack of data. Two wells (M17 and M24) were drilled into backfill, but difficulties in completing them prevented proper grouting of the annuli.

Well M17 was drilled into backfill at the southwest end of the Jackpile pit (fig. 3). The water-surface altitude was 5968 ± 1 ft at a pond about 500 ft north of the well in August, 1981. This was within 1 ft of the water level in the well. The greater head at these sites was not determined, because of the large error range in pond-surface altitude. Water may be flowing through backfill northward toward the pond, or from the pond toward lower areas to the west or south.

Well M24 is located at the north end of the South Paguate pit (fig. 3), and had a water-level altitude at 5981 ft in June, 1981. The water-level altitude is greater than that of the water surface in the lowermost pond in the pit, and greater than heads in the Jackpile sandstone near the well. Well M24 was drilled through backfill into what was formerly a holding pond for water pumped from mine workings (Hydro-search, Inc., 1979 and 1981). The water level may represent: ground-water mounding, or perched water, due to the holding pond; local recharge to the backfill, or; surface flow down the well annulus.

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Flow from the Rio Paguate to well M24 is not likely, because the water table in the alluvium was at altitude 5970 ft in March, 1979 (Hydro-search, Inc., 1979) at a point about 1500 ft downstream from wells M23 and P4. Discharge from the backfill at well M24 is probably toward the South Paguate pit, toward the Rio Paguate, or both.

No wells are completed in waste piles, so it is not known if the piles are unsaturated, periodically saturated, or constantly saturated. Runoff was observed flowing into small cavities atop two waste piles during a period of heavy rainfall, indicating much of the recharge is probably through very permeable vertical channels below surface depressions, rather than uniform infiltration over the surface of the piles. No seepage faces were observed at the bases of the piles during dry weather, indicating: saturation may be limited, and of short duration, or; flow may be vertical through the bases of the piles to the underlying bedrock or alluvium.

A hydraulic conductivity of 190 ft/day was reported for waste rock at well M24 by Hydro-search, Inc. (1981). The waste piles may have large enough hydraulic conductivity so that infiltrating water is discharged rapidly, preventing long-term saturation.

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WATER BALANCE

A water balance is useful for estimating evapotranspiration in the Rio Paguate drainage basin. A general form of the water-balance equation may be written as: $P = R + \Delta GW + U + ET$, where P is precipitation, R is runoff, ΔGW is change in ground-water storage, U is underflow, and ET is evapotranspiration.

The change in ground-water storage is assumed to be negligible on an annual basis. Total underflow is approximately equal to underflow through alluvium, as described previously. The U is therefore about 40 ft^3/s-days annually, which is equivalent to about 0.01 in/year over the 107 mi^2 drainage area above the gaging station. The underflow was added to runoff, and the sum subtracted from rainfall to estimate ET for water years 1977 through 1980 (table 16). Water losses by evapotranspiration are very large, constituting about 98 percent of rainfall.

Table 16. Water balance for the Rio Paguate drainage basin above the gaging station located below the Jackpile mine. Values are in inches/year, except numbers in parentheses are percent of rainfall.

Water Year	Rainfall	Runoff plus underflow	ET*
1977	8.38	0.197	8.2 (98)
1978	7.90	0.147	7.7 (97)
1979	11.60	0.179	11.4 (98)
1980	9.85	0.120	9.7 (98)
Mean	9.43	0.161	9.2 (98)

*Evapotranspiration.

WATER QUALITY

The available data from water analyses range from poor to good, based on cation-anion percent differences. The differences usually exceed 5 percent; many range from 10 to 50 percent, and some are over 60 percent. Reliability of much of the data is therefore questionable.

Surface-water and ground-water sampling sites are shown on figure 9. Most ground-water samples were obtained from older wells in the mine, and do not include the recently drilled "P"-series or "M"-series wells.

Water types and dissolved solids

Stiff diagrams were used to determine water types. Water in the Rio Moquino is a sodium-calcium-magnesium-sulfate type. Water in the Rio Paguate is a sodium-bicarbonate type above the confluence with the Rio Moquino. Below the confluence, the water in the Rio Paguate is of the same type as in the Rio Moquino.

The mean concentrations of total dissolved solids are about 1800 to 1900 mg/L in the Rio Moquino (table 17). They range from 575 to 700 mg/L in the Rio Paguate above its confluence with the Rio Moquino, and are about 2000 mg/L below the confluence. Mean concentrations of total dissolved solids in ground water range from 900 to 1500 mg/L.

Sulfate concentration is the limiting factor for use of water in most of the mine area. The water in the Rio Moquino is high in sulfate before it reaches the Jackpile mine. This high-sulfate water dominates the water quality in the Rio Paguate below its confluence with the Rio Moquino. Above the confluence of the streams, water of the Rio Paguate is of good quality. The water in the Rio Moquino and lower reaches of the Rio Paguate is useable for livestock, and for irrigation of some crops semi-tolerant or tolerant to salinity.

Table 17. Mean concentrations of total dissolved solids in water from the Jackpile mine area.

Sampling site	Total dissolved solids (mg/L)
Rio Paguate upstream	less than 575
Rio Paguate above confluece	less than 700
Rio Moquino upstream	1600
Rio Moquino above confluence	1900
Rio Paguate at ford crossing	2000
Rio Paguate at Paguate reservoir	2000
Well number 4	900
New shop well	1400
Old shop well	1500

Although the water quality is poor in the Rio Moquino and lower reaches of the Rio Paguate, as compared to areas of greater rainfall, it is better than in other streams within a 60 mi radius of the mine. Water-quality data have been collected at the Rio Puerco near Bernardo for 34 years, and show persistent salinity.

Minor elements

Concentrations of all minor elements were low in water flowing through the mine, and were essentially constant during the period of sampling. The concentrations of minor elements in water upstream and downstream from the Jackpile mine were below maximums established by the Environmental Protection Agency (1975 and 1977) for public water supply, agricultural, and industrial use, except in a few cases where one or more minor constituents limited use of the water for public supply or irrigation.

A few isolated samples exceeded the recommended limit of 0.05 mg/L for manganese in a public supply. A sampling point on the Rio Paguate above the Jackpile mine contained 0.078 mg/L manganese on January 29, 1979, and a sampling point on the Rio Paguate below Jackpile mine contained 0.22 mg/L manganese on November 1, 1977.

A sample taken from well number 4 contained 1 mg/L of boron in July, 1977, as did another sample from the new shop well. These concentrations restrict use of the water for irrigation, except for crops semi-tolerant or tolerant to boron. Samples from the old shop well contained a mean concentration of 0.157 mg/L of selenium, which considerably exceeds the 0.010 mg/L limit recommended for use as a public supply.

Radionuclide concentrations

Concentrations of uranium and radium 226 increase downstream in the Rio Paguate and Rio Moquino, as these streams cross the Jackpile mine. Table 18 shows the means of these constituents, for both surface and ground water. Analyses that show "less than" a given value are not included in the means.

All of the means in table 18 are less than the maximum permissible concentrations for uranium and radium 226 (both 5 picocuries per liter) in a public water supply, as proposed in the U.S. Environmental Protection Agency (1981). No single uranium determination exceeded the permissible limits. Radium 226 concentrations were within permissible limits at the upstream sites, but numerous determinations immediately above the confluence of the Rios Paguate and Moquino exceeded the limits. Sites below the confluence also had many values exceeding the limits. The gaining reaches of the two streams appears to be the principal source of high radium 226 concentrations.

A few samples were analyzed for thorium 230, and concentrations were less than the maximum permissible concentrations of 2000 picocuries per liter.

Table 18. Mean concentrations of uranium and radium 226 in water from the Jackpile mine area.

Sampling site	Uranium (mg/L)	Radium 226 (pCi/L)
Rio Paguate upstream	0.008	0.36
Rio Paguate above confluece	0.160	3.89
Rio Moquino upstream	0.007	0.34
Rio Moquino above confluence	0.051	1.73
Rio Paguate at ford crossing	0.266	4.31
Rio Paguate at Paguate reservoir	0.210	1.18
Well number 4	0.005	0.54
New shop well	0.008	2.19
Old shop well	0.112	2.13
P-10 well	0.0036	0.82

HYDROLOGIC CONDITIONS AFTER RECLAMATION

Part of the pit backfill will saturate after reclamation. The water will discharge to streams, and to adjacent strata. Saturation will result from: the end of pit-water use for road conditioning, considerable decrease in evaporation of pit water, discharge from bedrock, and local recharge. The water in backfill at the Paguate pits will discharge primarily to the Rio Paguate, because only permeable waste rock separates the pits from the stream. Discharge from the Jackpile pit will be to the Jackpile sandstone, because the backfill is enclosed by this strata. Heads in the Jackpile sandstone will increase due to saturation of backfill, and the eventual end of pumping from underground mines.

Waste piles are different hydrologically from backfill, in that they receive only local recharge. Discharge from the piles may be along the ground surface, or into underlying alluvium or bedrock.

Pit backfilling is necessary in order to reduce radon exhalation from the part of the Jackpile sandstone exposed by mining. Flow through both backfill and waste piles is considered particularly important, because: (a) water flowing through waste rock may contain elevated levels of dissolved materials, due to increased surface area exposed on the rock as the result of mining, and due to increased solubility of minerals in the rock as a result of their oxidation, (b) if long-term ponding results from part of the backfill being below the level of saturation, animals using the ponds could injest abnormally large quantities of dissolved materials, and (c) increased levels of dissolved materials could enter aquifers and streams.

Flow through backfill

The Rio Paguate gains water from the alluvium, both upstream and downstream from the Paguate pits. A well used for public supply at Paguate village is completed in alluvium of the Rio Paguate, and occasionally flows (Lyford, 1977), indicating discharge to the stream above the mine. Gains in streamflow below the Paguate pits, and losses between the pits, are described by Hydro-search, Inc. (1979). The present loss of stream water between the two pits is probably due to infiltration of the permeable backfill underlying the stream. It is therefore reasonable to assume that, prior to mining, the Rio Paguate was a gaining stream along its length from Paguate village at least to its confluence with the Rio Moquino.

Ground water will attempt to reach equillibrium at pre-mining levels after reclamation. The downstream part of the backfill underlying the Rio Paguate will thererfore probably saturate to stream level. The stream would then be the direct hydraulic control for discharge from backfill in the Paguate pits. Discharge from Jackpile pit backfill would be through the Jackpile sandstone, and most of the water will probably enter the alluvium and the Rio Paguate west, and possibly south, of the pit. The level of the Rio Paguate would therefore be the ultimate hydraulic control for water levels in backfill at the Jackpile pit.

Conceptual models are shown for the South Paguate pit (fig. 10), and the Jackpile pit (fig. 11). Flow through the North Paguate pit would be similar to that for the South Paguate pit, except that discharge toward the stream would be southward. The generalized section through the South Paguate pit is from the southernmost edge of the pit (southeast of well P6) to the Rio Paguate upstream from well P4. The generalized section through the Jackpile pit is from the west edge of Gavilan Mesa, through well site M18, to the Rio Paguate.

Positions are approximate on figures 10 and 11 for: the water table; level of proposed backfill; and, particularly, the bedrock surface beneath backfill. Mean thickness of backfill beneath the Rio Paguate is assumed to be about 30 ft. Cross section number 12 by Anaconda Copper Company ("Jackpile-Paguate Mine Additional Cross Sections 1-19", undated) shows backfill under the stream as 40 ft deep. Well site P4 is underlain by 16 ft of fill (Hydro-search, Inc., 1979). The contact of the Jackpile sandstone and the underlying mudstone unit of the Brushy Basin Member is at ground level west of the Jackpile pit, near the Rio Paguate. The Jackpile sandstone has been removed by erosion near the south end of the Jackpile pit.

Infiltration of backfill will be from: runoff; direct precipitation, and; discharge from bedrock, particularly the Jackpile sandstone. Discharge will be to the Rio Paguate at the the Paguate pits, and to the Jackpile sandstone - alluvium - Rio Paguate at the Jackpile pit. Discharge at the south end of the Jackpile pit could also be through the mudstone unit of the Brushy Basin Member.

Ponding will probably result if backfill in the Paguate pits is below the level of the Rio Paguate adjacent to the pits. Evapotranspiration may be sufficient to prevent long-term ponding if the level of backfill is at stream level, but occasional ponding could occur during periods of low evapotranspiration or large rainfall. Little or no ponding will occur if the backfill is several feet above stream level. The altitude of the stream is about 6010 ft at the upstream end of the backfill and at about 5975 ft at the downstream end of the backfill. The height of the water table in backfill is determined by recharge to the pits and discharge to the Rio Paguate.

Assuming inflow is equal to outflow at the Paguate pits, the general equation for recharge-discharge may be written as: $K_jI_jA_j + P = K_bI_bA_b + ET$, where; K and I are terms described previously, A is cross-sectional area perpendicular to flow, subscripts "j" refer to the Jackpile sandstone, subscripts "b" refer to the backfill, P is water added to the pit by direct precipitation and runoff, and ET is evapotranspiration. A linear approximation of the height of the water table is described by the product I_bD for given distances D upgradient from the stream.

Values for most factors in the equation above are known, or can be reasonably estimated. Little data are available regarding ET however. The average ET for the entire Rio Paguate drainage basin is about 98 percent of rainfall, as described in a previous section. This percent could be quite different locally, particularly where direct precipitation and runoff from steep pit walls may quickly infiltrate permeable backfill.

The position of the water table in backfill at the Jackpile pit is controlled by factors described for the Paguate pits, and also by discharge through: the Jackpile sandstone; alluvium, and; possibly the mudstone unit in the Brushy Basin Member. Flow is therefore across at least four boundaries, as opposed to two in the Paguate pits. After reclamation, ground-water levels in backfill will attempt to reach equillibrium between heads now in Gavilan Mesa, and the levels of the streams adjacent to the pit. The Rio Moquino is at an altitude of about 5925 ft west of the Jackpile pit, and the Rio Paguate is at an altitude of about 5850 ft near the southwest end of the pit.

Computer flow models should be used to approximate water-table altitudes in backfill after reclamation, and to estimate the volumetric rate of discharge. The ultimate recovery levels of ground water are not known precisely, so discharge from bedrock would have to be estimated. Error would probably not be significant if discharge is assumed to be from the entire thickness of the Jackpile sandstone. Estimates would have to be made for modeling local infiltration and recharge to pits, because no data are available. Worst-case conditions could be examined by using extreme rainfall events, such as those given in table 3, and low evapotranspiration. The hydraulic conductivity of 190 ft/day obtained at well site M24 (Hydro-search, Inc., 1981) could be used for backfill. The hydraulic conductivities given in the present report could be used for the Jackpile sandstone, and for the alluvium.

Flow through waste piles

The unnamed valley on the east side of Gavilan Mesa is dry except for short periods with large rainfall. At least the upper part of the alluvium is therefore unsaturated. The waste piles blocking the valley are probably also dry much of the time, because no discharge is visible at their downstream end. Water infiltrates the alluvium and waste rock however, and is partly due to occasional ponding at the faces of the piles.

Wetting fronts move more rapidly through fine-grained materials than through coarse-grained materials. Therefore, ponded water at the waste piles may enter the alluvium more rapidly than the waste rock. The volume of water entering alluvium and waste rock, and the extent of saturation of the waste rock, at the blocked valley would probably best be determined by constructing a flow model of the site. The values given in table 13 for depths of ponded water provide some of the boundary conditions for the model. Other conditions are not known, such as: thickness of alluvial deposits, depth to water table, and unsaturated hydraulic conductivities. These would have to be estimated, or determined by field investigation.

Numerous waste piles are located outside of valleys, and are not part of pit backfill. Recharge to the piles will be from direct precipitation. Reclamation plans call for the piles to be flat-topped, with terraced sides and berms to reduce erosion. The proposed design promotes infiltration.

The alternative to the proposed form of reclamation would be to have waste piles mound-shaped, with no berms or terraces. Infiltration of the piles would then be reduced. Erosion of soil cover, and extensive gullying on the sides of the piles would probably result, however. The accelerated erosion would transport radionuclide-bearing sediments to adjacent streams, to the Paguate reservoir, and perhaps to the Rio San Jose.

Assuming waste piles are reclaimed as flat-topped structures with terraces and berms, infiltration will be greatest in the basins formed by the structures. Waste piles presently reclaimed show highly transmissive vertical channels at the lower parts of the basins. Runoff from adjacent higher areas rapidly infiltrates these vertical channels.

Infiltrating rainfall and runoff may flow through the piles so rapidly that saturation of the waste does not occur, or is short-term. The time of water contact with the waste may therefore be short, so that solution of minerals from the waste is minor. No data are available regarding extent of saturation or water quality in waste piles, however.

Flow through waste piles should be modeled, using dimensions of a typical waste pile. The lower boundary of the pile may be alluvium, or may be bedrock. As described previously, infiltration rates would have to be estimated for the model.

PROPOSED MONITORING

Surface water

Sampling points presently used for surface-water quality (fig. 9) should continue to be used, except possibly for the one at the "ford crossing". They are properly located for determining water quality at hydrologically important points, and should show changes in quality as water moves through the mine. Four additional locations are suggested for sampling. One of these may be substituted for the "ford crossing" sampling point. Their locations, and reasons for sampling the locations, are described below.

One sampling point should be located at the U.S. Geological Survey gaging station, where the Rio Paguate flows beneath the railroad spur. Reasons for establishing this sampling point are: (a) some water from waste dumps C, D, E, F, and G, and possibly some water from the Jackpile pit, may discharge to the Rio Paguate below the ford crossing sampling point, (b) discharge data from the gaging station may be used to compute a dissolved-constituent load from the mine, and (c) the location is sufficiently far enough from disturbed areas so that samples from the site may be considered as reflecting most influence from mining activity (except possibly for some flow from the Jackpile pit via alluvium). This sampling point could be substituted for that at the ford crossing.

A sampling point should be established above Paguate reservoir, north of where swamp-like conditions exist due to sedimentation in the reservoir. No data are available reagrding flow through alluvium to the Rio Paguate below the mine, but ground-water could discharge to the stream between the southern mine boundary and the Paguate reservoir. The ground-water discharge could dilute, or possibly increase, ion concentrations in surface water discharging from the Jackpile mine. The samples presently taken at the dam of Paguate reservoir probably reflect considerable evapotranspiration, and are probably not representative of freely flowing water to the north of the the reservoir.

Two sampling points should be located on the Rio San Jose; one directly above, and one directly below, its confluence with the Rio Paguate. Results of analyses from these samples could be compared, to determine influence of flow from the Rio Paguate on quality of water in the Rio San Jose.

Sampling frequency and types of analyses

Water-quality samples should be taken initially about once every 2 months. If trends can be established for given discharges, sampling frequency might later be extended to once every 3 or 4 months.

Surface-water quality is expected to be much more variable than ground-water quality, due to rapid influence by rainfall and evapotranspiration. Care should be taken to obtain samples at various stream discharges. Minimum concentrations of dissolved ions may be expected during the latter periods of high discharge, and maximum concentrations during the latter periods of low discharge. Loads of dissolved constituents should be computed by using stream-discharge data.

Types of analyses should be the same as presently done for samples from the mine, that is; common ions, total dissolved solids, minor elements, radium 226, radium 228, thorium 230, and uranium. Temperature, specific conductance and pH should be measured in the field. Titration for alkalinity should also be done in the field.

Duplicate samples should be taken at least once a year. One set of duplicates should be analyzed by a laboratory independent from that normally used, for the purpose of comparing laboratory results.

Ground water

Water-quality data collected from existing wells in the Jackpile mine will probably be of limited use, because: (a) most wells are not located in areas where data should be collected, and (b) water-quality data may not be representative of that at the intended sampling point, due to excess shrinkage of cement at the wells and resultant leakage of water from upper to lower zones. Cement shrinkage in well annuli may have been considerable, as evident by several feet of void annular space near ground surface at some wells.

Void annular space may fill with runoff, resulting in infiltration of water from near surface down the cement-rock or cement-casing interfaces. Even if the void space was again cemented at existing wells, the integrity of the deeper cement bonds is questionable, and water from upper strata may move to lower strata. Extensive cement shrinkage indicates excess water has moved from the cement during crystallization, and this may have resulted in permeable channels forming along the bonding interfaces. Water-quality data from the wells may therefore not be representative of that in the strata to which the well is open. Suggested cementing procedures and materials for sealing annuli of monitoring wells are given in appendix 3. If some existing wells are to be used for monitoring, the wells should be pumped until pH and specific conductance of the water have stabilized before samples are taken.

One of two methods may be used to monitor ground-water quality at the Jackpile mine. The first is to determine only the change in quality of ground water that has flowed through the mine. It is called limited monitoring in this report. This method would neither describe the sources of possible contaminants, nor describe areal changes in water quality. A second method is to monitor the ground water in such a way that specific sources of possible contaminants are determined, and spatial distribution of the possible contaminants are described. It is called thorough monitoring in this report.

Limited monitoring

Probably as few as three well sites would be needed to monitor only the change in quality of ground water flowing from the open-pit mining area. One well site should be at the southern perimeter of the mine, about 2000 ft east of the stream-gaging station shown on (fig. 3). One well should be completed in alluvium, and one well completed in the sandstone unit of the Brushy Basin Member at this location. The second well site should be at the southeast corner of the mine, about 3000 ft southeast of waste dumps C, D, E, F, and G. Two wells should be completed at this location, as described for the site near the gaging station. A third well site should be at the north end of the mine, for the purpose of establishing natural water quality. A suitable site would probably be near the Rio Moquino, about 1000 ft north of well M9. Again, one well should be completed in alluvium and one well completed in the sandstone unit of the Brushy Basin Member.

After underground mining has ended, a well should be completed in the sandstone unit of the Brushy Basin Member in Oak Canyon to monitor possible flow from the underground mining area.

Thorough monitoring

Thorough monitoring involves much more extensive well construction than would be done in limited monitoring. Not only would more wells be installed, but difficulties should be expected during construction of wells to be completed in backfill.

Monitoring wells should be constructed in pit backfill after all planned backfill has been placed. Water-quality data from the wells can be used to describe probable maximum concentrations of dissolved substances resulting from reclamation and discharging to adjacent rocks and streams. At least one well should be located at each of the following sites: the north side of the South Paguate pit; the south side of the North Paguate pit, and; the west side of the Jackpile pit, where the contact of the Jackpile sandstone and mudstone unit of the Brushy Basin Member is below ground level. Ideally, the wells should be positioned at the downgradient end of the backfill. Gradients could be determined by installing several small-diameter wells in each pit, and periodically measuring the water levels in these wells. Because pit backfill may not saturate to equillibrium levels for several years, more monitoring wells may have to be constructed later at the down-gradient areas, in addition to the minimum of three described above.

Multiple-well locations are described in the following paragraphs. The wells should be clustered: that is; distance between wells at any one location should not be more than about 30 ft.

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Wells for monitoring quality of water discharging from the pits should be located as follow. Three wells west of the Jackpile pit, near the Rio Moquino: one completed in alluvium; one completed in the upper part of the Jackpile sandstone, and; one completed at the base of the Jackpile sandstone. Two wells should be completed about 2000 ft east of the gaging station, as described in the previous section. Also, two wells should be installed at the southeast corner of the mine, as described in the previous section. Four wells should be completed near existing wells M23 and P4: one in backfill; one in alluvium; one near the top of the Jackpile sandstone, and; one near the base of the Jackpile sandstone.

If water quality is similar in backfill of the South Paguate pit to backfill of the North Paguate pit, the proposed wells near existing wells M23 and P4 should suffice. If water quality is different in backfill of the two pits, an additional set of four wells should be constructed north of the Rio Paguate, at the south end of the North Paguate pit. These wells should be completed in the same strata as described for the proposed wells near M23 and P4.

Waste piles are too numerous to monitor separately, from an economic viewpoint. The reclaimed part of "T" dump is suggested as a representative site. Four wells should be installed at the east side of the dump, near the Rio Moquino: one completed in waste rock; one completed in underlying alluvium (if present); one in the upper part of the Jackpile sandstone, and; one near the base of the Jackpile sandstone.

At least one monitoring well should be installed at the dumps blocking the valley east of Gavilan Mesa, because water occasionally ponds in this area. The well should be located in the valley, immediately downstream from the piles, and completed a few feet below the water table. The water table may be in the alluvium, or may be in the underlying bedrock. Ideally, two other wells should be located at the upstream end of the dumps, near the area of ponding. One of the wells should be completed in waste rock, and the other completed a few feet below the water table.

Natural water quality should be determined by installing three wells about 1000 ft north of existing well M9. One well should be completed in alluvium, one in the Jackpile sandstone, and one in the sandstone unit of the Brushy Basin Member.

Sampling frequency and types of analyses

Initial sampling frequency should be about once every three months. If trends can be established after several sampling periods, the frequency could be changed to about twice-yearly. If samples are collected two times a year, one sampling period should be in late winter, and the other in late fall. Local recharge in the mine area is probably least in winter, and greatest in summer.

Types of analyses should be the same as presently done for samples from the mine, as explained in the section regarding proposed surface-water monitoring. Temperature, specific conductance and pH should be measured in the field. Titration for alkalinity should also be done in the field. Duplicate samples should be taken at least once a year for the purpose of comparing laboratory results.

SUMMARY AND CONCLUSIONS

About 2600 acres of land are to be reclaimed at the Jackpile mine, located on the Laguna Pueblo Indian Reservation in norhtwestern New Mexico. Uranium was mined at ground surface from the Jackpile sandstone in the Morrison Formation, during the period 1953 to 1980. Reclamation plans include partial backfilling of three open pits to reduce radon exhalation, and modifying the shape of waste-rock piles located outside of the pits.

The pits are as much as 200 to 300 ft below the adjacent ground surface, and encompass about 1,015 acres. Piles of waste rock are as much as ~~200~~ 350 ft in height, with most about 50 to 75 ft. Thirty-two piles of waste rock cover 1,266 acres. Planned reclamation includes making waste piles flat-topped, so as to resemble the mesas in the area. Terraces and berms are to be constructed on the sides of the piles to reduce erosion.

Primary hydrologic concerns are that oxidation and large surface area of rock fragments in backfill and waste piles may promote above-normal dissolution of rock minerals, including minor elements and radionuclides, by water flowing through the waste. Virtually no data exist regarding quality of water passing through the waste rock, however. Water from waste rock will discharge to: adjacent streams, and; adjacent aquifers, principally the alluvium and the Jackpile sandstone.

The topography of the Laguna area is mountainous, with numerous spectacular mesas. Altitudes range from 11,300 ft at Mount Taylor to 5,700 ft on the Rio San Jose south of the Jackpile mine. The climate is arid, with mean annual rainfall of 9.5 in. Surface-water evaporation is about 76 in/year, as measured by the pan evaporation method. Evapotranspiration losses are about 98 percent of rainfall.

The Rio Paguate flows through the Jackpile mine, and the Rio Moquino is tributary to the Rio Paguate in the northern part of the mine. The Rio Paguate flows into Paguate reservoir about 4 mi below the southern mine boundary, then enters the Rio San Jose about 0.5 mi south of the reservoir. Mean daily discharge of the Rio Paguate is about 1.2 ft^3/s at the south end of the mine, about 50 percent of which is base flow. Peak discharge during large floods ranges from about 1,520 ft^3/s once every 5 years to about 10,500 ft^3/s once every 500 years, as estimated by the basin-characteristics method.

The Rio Paguate flows over waste rock between the north and south Paguate pits. Present loss of stream water between the Paguate pits is due to infiltration of the backfill, and lowering of the water table in the area due to loss of water from pits and pumpage from underground mines.

Ponding may occur where waste dumps block an arroyo at the east side of the Jackpile mine. Maximum depth of ponded water is estimated as 3.9 ft for a flood flow of one day at recurrence interval of 50 years. Depths are less than 2 ft for most flow periods and recurrence intervals. Water from the pond will infiltrate underlying alluvium and waste rock at the upstream end of the dumps.

Sediment has nearly filled the Paguate reservoir since construction of the dam in 1940. Sediment yield due to mining is less than about 1 percent of total sediment yield in the basin, and sediment deposited in the reservoir due to mining is estimated as less than 0.2 acre-ft/year. The small sediment contribution resulting from mining is due to the externally draining mine area constituting only about one percent of the 107 mi^2 drainage area in the Rio Paguate basin.

The recharge rate in the Rio Paguate drainage basin is about 0.1 in/year, based on the sum of base flow and underflow through alluvium. Rates may vary locally with elevation, ground slope, rock type, and distribution of alluvium and aeolian deposits. Recharge to rocks in the Jackpile mine is from high areas on the flanks of Mount Taylor to the west, and probably from Mesa Chivato to the north. Some recharge may occur locally in the mine. Regional ground-water flow is southward toward the Rio San Jose, and eastward toward the Rio Puerco. Most of the local flow in alluvium and in the Jackpile sandstone discharges to mine pits, to underground mines presently being dewatered, and to the Rio Paguate and Rio Moquino. Some ground-water may flow from the mine via alluvial and aeolian deposits, and from rocks in the Brushy Basin Member.

The hydraulic conductivity is about: 22 ft/day for the alluvium, and; 0.3 ft/day for the Jackpile sandstone, and for a sandstone bed in the underlying part of the Brushy Basin Member. Mudstone beds approximately 100 ft thick separate the deeper sandstone from the Jackpile sandstone. Poor hydraulic connection between the two sandstone strata indicates that the mudstone unit is a lower hydrologic boundary in the mine area. Head differences between the two sandstone beds indicate downward flow of some water from the Jackpile sandstone, however.

Water in the Rio Moquino is a sodium-calcium-magnesium-sulfate type, with total dissolved solids of about 1,800 mg/L. Water in the Rio Paguate above the Rio Moquino is a sodium-bicarbonate type, with total dissolved solids of about 600 mg/L. Below the confluence of the streams, the water in the Rio Paguate is of the same type as in the Rio Moquino, with total dissolved solids of about 2,000 mg/L. Mean concentrations of total dissolved solids in samples from ground-water sampling locations range from 900 to 1,500 mg/L.

Sulfate concentration is the limiting factor for public use, and for some agricultural uses, of stream water in the mine area. The water in the Rio Moquino is high in sulfate before it reaches the Jackpile mine, and this high-sulate water dominates the water quality in the Rio Paguate below its confluence with the Rio Moqino. Concentrations of minor elements were below maximums established for use as a public water supply, and for agricultural and industrial use, except for occasional samples in which manganese, boron and selenium exceeded the limits for use as a public supply.

Mean concentrations of uranium and radium 226 increase through the mine area at various surface-water sampling sites. They are less at Paguate reservoir than at the southern part of the mine, but they are greater at Paguate reservoir than at sampling sites above the mine. None of the mean values exceeded recommended maximum concentrations for public use. No individual stream-water samples exceeded recommended limits for radium 226 above the mine. Numerous individual samples obtained immediately above and below the confluence of the Rios Paguate and Moquino exceeded the recommended maximum concentration of radium 226 for public consumption. Concentrations in surface water are apparently changed by ground-water inflow near the confluence of the two streams. No samples exceeded recommended limits for throium 230, for use as a public supply.

Part of the backfill will saturate after reclamation. The water will discharge to adjacent strata, and to streams. Discharge from the Paguate pits will primarily be from bacfill to the stretch of the Rio Paguate adjacent to the pits. Most discharge from the Jackpile pit will probably be from backfill to the Jackpile sandstone, then to alluvium and to the Rio Paguate. Some discharge from the Jackpile pit could be to strata underlying the Jackpile sandstone.

At equillibrium, the altitudes of the water tables in pit backfill are partly controlled by the altitude of the Rio Paguate adjacent to the pits. Other factors controlling the altitudes of the water tables are: recharge rate to the backfill, and; hydraulic conductivity of the backfill, alluvium, Jackpile sandstone, and mudstone unit of the Brushy Basin Member. Computer flow models should be made of the pits to estimate post-relamation equillibrium levels of the water tables in backfill.

Waste piles are different hydrologically from backfill, in that they receive only local recharge. Recharge will be from direct precipitation on most piles, and basins formed by berms around terraces will promote infiltration. Recharge to the upstream part of the backfill blocking the arroyo east of Gavilan Mesa will be due to ponding at the faces of the dumps. Virtually no information exists regarding extent of saturation in waste piles, however. Previous studies showed waste rock as having a hydraulic conductivity of 190 ft/day. The waste rock may be permeable enough so that saturation is limited, and of short duration. Discharge from the piles may be to ground surface, or to underlying alluvium and bedrock. Computer flow models should be made of a typical waste pile, and of the waste piles blocking the arroyo east of Gavilan Mesa.

After reclamation, most shallow ground-water will probably discharge to streams in the mine. Remaining ground water will probably flow to the south and east, where erosion has removed the northwest-dipping Jackpile sandstone from the valleys. Remaining shallow ground water from the mine will therefore move primarily through allvuium, and some will move through mudstone and sandstone beds which underlie the alluvium.

Four surface-water monitoring stations should be established, in addition to those presently sampled. Their locations should be as follow: at the gaging station on the Rio Paguate at the south end of the mine, on the Rio Paguate immediately north of Paguate reservoir, on the Rio San Jose immediately upstream from the Rio Paguate, and on the Rio San Jose immediately downstream from the Rio Paguate. The present sampling station at the "ford crossing" could be discontinued.

Surface-water-quality samples should be collected about once every two months, and at different discharges. If trends can be established for given discharges, sampling frequency could later be extended to once every three or four months. Loads of dissolved constituents should be computed using stream-discharge and water-qualtity data collected at the gaging station. Duplicate sampling should be done at least once a year, to compare laboratory results. Types of analyses should be: common ions, total dissolved solids, minor elements, radium 226, radium 228, thorium 230, and uranium. Temperature, specific conductance, pH, and alkalinity should be measured in the field.

Quality of ground water may be monitored as: "limited monitoring", in which only the change in water quality is determined as the ground water flows from the mine, or; "thorough monitoring", in which specific sources of possible contaminants are determined, and spatial distribution of the possible contaminants are described. As few as three well locations are needed for limited monitoring: one at the northern part of the mine for determining natural water quality, and; two at the south and southeast ends of the mine to determine changes in water quality which would likely be due to mining. Paired wells should be completed at each location as follow: one in alluvium, and one in the sandstone strata below the mudstone unit in the Brushy Basin Member. Many more well locations are required for thorough monitoring, and are described in the text of this report.

Ground-water-quality samples should be collected initially about once every three months. If trends can be established, the frequency could be changed to twice-yearly. Types of analyses, field measurements, and duplicate sampling should be the same as described above for surface water.

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Appendix 1. Mean monthly and mean annual discharge for Paguate Creek near Laguna, New Mexico. All values are in cubic feet per second.

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
1937	-	-	-	-	-	1.45	1.77	0.73	0.61	0.66	0.77	0.70	-
1938	0.78	0.98	1.15	1.16	1.07	1.18	1.24	1.21	0.91	0.82	0.35	1.03	0.99
1939	0.76	0.92	1.04	1.06	1.04	1.58	2.09	0.85	0.48	0.93	0.88	0.62	1.02
1940	0.85	1.10	1.22	1.16	1.62	1.18	1.14	0.92	0.47	0.80	0.76	1.06	1.02
1941	0.84	1.67	1.42	1.18	1.59	5.92	12.6	14.7	1.51	0.71	0.93	2.42	3.80

Appendix 2. Mean monthly and mean annual discharge for Rio Paguate below Jackpile mine near Laguna, New Mexico. All values are in cubic feet per second.

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
1976	-	-		-		-	1.21	1.05	0.48	0.38	4.18	0.79	-
1977	0.67	1.07	1.15	1.66	1.68	1.66	1.53	2.00	0.54	0.69	1.71	3.40	1.48
1978	0.47	0.61	0.95	1.55	2.09	1.34	0.81	0.98	0.37	0.28	3.33	0.20	1.08
1979	0.22	1.59	0.80	1.99	2.66	3.57	1.36	1.13	0.56	0.16	1.26	0.76	1.33
1980	0.30	0.69	0.65	1.59	1.77	1.80	0.82	0.29	0.12	0.047	0.095	2.28	0.87

Appendix 3. Suggested procedures for cementing annuli of monitoring wells.

Monitoring wells should be cemented by commercial cementing firms, rather than by drilling contractors, because they have equipment and expertise not normally available on drilling rigs. Cement should be injected down the inside of the casing, followed by an air or water drive to force the cement up the wells annulus, from the bottom of the cemented section to ground surface. The exterior of the well casing should be slightly rusted, and have centralizers attached every 20 to 40 ft. Modern cementing equipment should be used, including a high-pressure cementing head attached to the top of the casing, float shoe at the bottom of the casing, and top and bottom cementing plugs.

A 50 percent pozzolan, 50 percent portland cement should be used to increase longevity of the cement bond, because the high-sulfate water in rocks at the Jackpile mine may cause rapid deterioration of solely portland cement. Additives of sodium chloride or gypsum cement should be used to provide at least 0.15 percent expansion. Water content should be minimal. It should be sufficient only to provide thorough mixing with the dry cement, and provide low enough viscosity to enable pumping down the inside of the casing. Bentonite may be used for improving flow rate during pumping, and for sorbing part of the excess water.

The water column used to drive cement out of the casing should be removed immediately after emplacement, so that micro-annular space does not develop as a result of later contraction of the casing.

Cementing will prove particularly difficult for wells that are completed in waste rock, and losses of some wells may be expected. Void sealants could be used in attempts to retain cement in the well annuli. If void space is so large that it is not possible to cement the annuli, it would probably be sufficent to divert rainfall and surface runoff from the wells. This may be accomplished by excavating a hole around the top of the well, and filling it with cement or concrete. The hole should be at least 2 ft deep at the well casing, at least 3 ft deep at its perimeter, and at least 15 ft in diameter. The surface of the cement should be sloped downward away from the casing.